AD_____

Award Number: W81XWH-10-1-0871

TITLE: Determination of Long Term Motor Control and Cutaneous Sensory Properties of a High Resolution Peripheral Nerve Interface Technology for Limb Amputees

PRINCIPAL INVESTIGATOR: David J. Edell. Ph.D.

CONTRACTING ORGANIZATION: InnerSea Technology Inc.
Bedford, MA 01730

REPORT DATE: December 2012

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
December 2012	Final	15 September 2010 – 14 November 2012

4. TITLE AND SUBTITLE

Determination of Long Term Motor Control and Cutaneous Sensory Properties of a High Resolution Peripheral Nerve Interface Technology for Limb Amputees

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-10-1-0871

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

David J. Edell, Ph.D.

E-Mail: djedell@innersea.com

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

InnerSea Technology Inc.
Bedford, MA 01730

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Methods for recording and stimulating through implantable microtube arrays that may be of clinical use were developed. 3D assembly methods were designed. High reliability electrode arrays were fabricated with CMOS and implant compatible processing. Interconnect and percutaneous connectors were designed and implemented including an adapter that allows wire bonding of the silicon microelectrode arrays and soldering of interconnects to the percutaneous connectors. Initial approaches to production of microtubes on wafers or devices were unsuccessful. Alternative approaches were devised but most were: too expensive for commercial feasibility; involved materials of unknown biocompatibility; or were low yield in practice. Some approaches required relatively expensive capital equipment which could not be justified for prototypes. Recent efforts resulted in identification of commercial approaches that would likely be feasible if developed. A low cost, single device "universal" casting method has recently shown promise and is currently being evaluated.

15. SUBJECT TERMS
Peripheral nerve interface long term micro electrode array amputee high reliability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			USAMRMC
U	U	U	UU	14	19b. TELEPHONE NUMBER *(include area code)*

Table of Contents

High Resolution Peripheral Nerve Interface

USAMRMC PROPOSAL NUMBER OR090772, AWARD NUMBER W81XWH-10-1-0871

INTRODUCTION:

In the original proposal, and through most of the work on this project, the following perspective was held: The subject of this research program is the development of a highly reliabile peripheral nerve interface that has the purpose of potentially returning full functional control and sensation for limb prostheses. Scope: Two questions were to be answered under the proposed work: 1) Will the mammalian peripheral nerve regenerate into MTAs when surrogate target tissues are provided as would be necessary clinically?; and 2) Will both efferent and afferent mammalian axons remain functional for providing motor and sensory functions?

While we were not successful in bringing along the necessary technology with sufficient speed and economy to be able to broadly define answers to these questions from our animal testing, we have developed the technology base sufficiently to enable application of the technology. Our preliminary prior work from 2005 is consistent with more recent results from ongoing research in other groups (notably Cambridge University). Taken together, sufficient results are now available to ensure that the Micro-Tube Array (MTA) approach will result in a highly robust, bidirectional peripheral nerve interface capable of providing long term closed loop motor control with high quality sensation.

An appropriate test structure would mimic that of the envisioned clinical device, which needs to be well defined before meaningful testing can be accomplished. A daunting factor was to find a way around the wiring/signal processing issues as a large number of independent signal acquisitions from the MTAs are required. A circuit approach was designed that can provide the low power neural data exchange that must exist for the peripheral nerve interface concept to function in a practical application. This circuit approach was designed to be consistent with the need for compression of raw neural data into physiological channels with very low bandwidth in order to conserve power while at the same time, enabling serial transmission of data which is likely the only practical alternative in a clinical system. This serial data exchange system then allows construction of 3D circuits which share power, signal and ground, thereby reducing the number of circuit interconnects to the minimum – 3.

Since a clinical system must be constructed in advance of any implant surgery, and since the nerve sizes and content vary widely by location, a “one size fits all” approach was included in the overall approach as this is the only practical way of approaching the problem. Intra-operatively, small fascicles can be readily grouped to form larger fascicles, while larger fascicles can be readily divided into smaller fascicles during implant surgeries.

In order to rigorously but fairly test the MTA approach, short term human trials are now favored over animal trials. We have designed animal experiments with sufficient statistical power to evaluate the MTA technology for amputees, but these are tedious, very time intensive and very expensive endeavors involving relatively large numbers of impaired animals. While such experiments can be accomplished with sufficient resources, they will not necessarily provide critical data (how well it will likely work in humans), but will clearly delay the realization of this technology and consume scarce resources. Human experiments will not only provide much more efficient testing of the premises, but will also ensure that at the end of testing, the value of the technology for applications within the human species will be fully ascertained. If the full complement of animal testing was accomplished (far beyond those outlined in the original proposal), these experiments and algorithm developments would still need to be repeated and expanded upon during human trials before clinical value could be weighed. Once human trials are underway, it may be that questions will arise that will be better resolved by series of experiments in animals. By then, it will be possible to directly relate results in human trials to those of animal testing to confirm or dissuade use of animal models to further the technology.

Moreover, the technology must be the same for both human and animal trials, simply to have sufficient neural control with closed loop feedback for evaluation. Relatively large numbers of channels are required for statistical validation. The simplistic one wire/electrode approach (originally proposed) is a heroic effort even once the devices exist because of the tedious nature of bringing large numbers of wires from peripheral nerves out through the skin. It can be done, and we have the experience and have designed the system, but it requires large resources of funding, personnel, and many years to accomplish.

A more rational plan would be to put whatever resources that can be identified into development of the technology to the point of clinical application, and then begin using it clinically. There are relatively few questions about the physical interface or circuit approaches, and the interpretive software should reside externally in any case. With this technology in hand, the most rudimentary processing would produce relatively high quality control signals that would be inherently "natural" in that they would derive from the same neuromuscular pathways that were disrupted by the amputation, so restoration of sub-conscious control and reflexes is possible. With the involvement of the human volunteers, development of more sophisticated closed loop systems, and sensation would rapidly follow since teams of software control engineers could then focus on these issues.

What is needed, however, is the MTA neural interface where the large populations of discrete motor axons that are necessary to construct a valid neural control output can be accessed, segregated and compiled into high fidelity control outputs. Access to large populations of discrete afferent pathways for sensory feedback and sensation are needed to provide the many sensory inputs that are required for even simple closed loops control and quality sensation.

Because of these considerations, difficulties with development of the MTA technology base, limited budget, and time, the focus of this grant necessarily became narrowed to development of the MTA technology base that would be suitable for clinical application. By "suitable" for clinical application, it is meant that the MTA technology is compatible with modern microcircuit technology, and that means are provided for enabling application of this microcircuit technology to the inner environment of peripheral nerves. These considerations are essential in order to efficiently and effectively exchange data with the axons involved in closed loop motor control and sensation. The work conducted under this grant provides a pathway for realization of this clinical system.

BODY:

While the progress was slow due to many contributing factors, the greatest impact on overall accomplishment was due to encountering numerous technical problems with the original approaches when applied to real devices that could lead to clinical technology. Alternative approaches were devised but were found to be: too expensive for commercial feasibility; involved materials of unknown biocompatibility that could not be readily substituted; or were low yield in practice. Some of the approaches required relatively expensive capital equipment which could not be justified for prototype attempts.

Original SOW (items not addressed highlighted:

1. Local IACUC Animal Studies approval
2. USAMRMC ORP review and approval of animal regulatory documents
3. Fabricate 2 test systems each consisting of:
   - 3.1. One 16 channel pre-amplifier, post amplifier, data acquisition interface; and one 16 channel optically isolated microstimulator with high resolution, low voltage control (for microtubes)
   - 3.2. Software for controlling stimulation and recording experiments in animals
   - 3.3. Restraint feeder for animals to allow early morning hand feeding while recordings are taken and to stabilize the animal during stimulation studies (in case of startle reflex).
4. Fabricate 5 implant assemblies each including:
   - 4.1.1. Two percutaneous 12 pin connectors

4.1.2. One bipolar cuff electrode for sciatic nerve
4.1.3. One bipolar recording electrode pair for recording from the peroneal muscle
4.1.4. One 16 electrode MTA with divided target tissue receptacle for motor and sensory
4.1.5. Three epidural/percutaneous electrodes
4.1.6. Implant 4 New Zealand White Rabbits with composite target tissue approach
4.1.7. One implant per day so the 4 animals will be implanted in 1 week.

5. Monitor performance (up to 3 months) of efferent and afferent pathways
   5.1. Animal is tethered using a cross-tied collar which will allow freedom of head and neck movements but constrains the animal so they cannot twist around and dislodge or chew on wiring.
   5.2. Record natural signals from efferent implants by rocking and rotating the animal back and forth and side to side to elicit all levels of activity possible.
   5.3. Sedate/anesthetize the animal and stimulate through afferent implants while synchronously recording and averaging from the epidural CEPs and also the efferent channels (looking for reflex activity). Determine stimulation thresholds and recruitment characteristics for each microtube. Check for evidence of neural damage by beginning at low level, running through increasing sequence, and then returning to lowest threshold level. Use high resolution voltage controlled stimulator.
   5.4. Plot signal amplitudes and selectivity of stimulation over time to identify trends.
   5.5. Compute the maximum, minimum, and mean dynamic range for the microtubes in the efferent and afferent categories separately.
6. Histologically evaluate all implants
   6.1.1. Perfuse animals, dissect and recover implants and target tissues
   6.1.2. Evaluate Histology
      6.1.2.1. Send samples to commercial laboratory for processing: Peripheral nerve – osmium myelin stain; Muscle – Masson trichrome; Dermis – hematoxylin/eosin
      6.1.2.2. Count and measure for each group of target tissues
      6.1.2.3. Number of microtubes containing myelinated axons
      6.1.2.4. Total number of myelinated axons within each MTA
      6.1.2.5. Number of axons within the target tissues
      6.1.2.6. Note the presence of muscle cells or dermal cells and vascularization of the targets
7. Compare results of efferent and afferent target tissues
   7.1. Percentage of microtubes occupied by myelinated axons for each group
   7.2. Average number of myelinated axons per occupied microtube for each group
   7.3. Total number of myelinated axons exiting the MTA for each group
   7.4. Stability of stimulation thresholds over time for each group
   7.5. Stability of dynamic range over time for each group
8. Prepare final report and publication of results
   8.1. Provide an assessment as to the feasibility of moving ahead with a larger study including clinical research and anticipated human performance based on these results.
   8.2. Publish study results for high resolution bi-directional peripheral nerve technology for amputees.

Year II Update Report:

Clinical implant CMOS compatible technology development

Production of MTAs onto CMOS compatible surfaces:

A search for a better mold material that could be micromachined eventually yielded three possibilities that were explored. While maintenance of the pristine surface of the silicone was a high priority, accomplishing the project and risking possible micro-biocompatibility issues was a tradeoff that had to be made. The following was determined:

1) Use a low molecular weight silicone lubricant or fluoropolymer lubricant to pre-coat the mold surfaces prior to casting the silicone. These are available as implantable materials, but it is doubtful that they have been evaluated for micro-biocompatibility issues. One low viscosity silicone and one low viscosity fluoropolymer fluid were procured from Nusil. Both of these fluids were absorbed into the silicone and did not provide release as hoped. The MED4-4220 readily displaced/absorbed these fluids from surfaces.
2) Use of a biocompatible refractory metal that can be laser micromachined to produce a controlled wall relief and smoother, pore free surface than polymers was explored. Molybdenum and tungsten both have somewhat water soluble oxides which should release during water soak, but again there is a potential for a micro-biocompatibility issue with residual oxide of Mo and W though both materials are well proven as implantable. A basic test of these materials was conducted on micro-roughened surfaces such as may be encountered with micromachining of trenches for casting. While silicones will release well from polished surfaces of these materials, the micro-rough surfaces held much better. Even gold on micro-rough stainless steel did not release well. It became apparent that real issue is the strength of the silicone relative to its elongation at the micro-level, and the strength of the silicon chips relative to the silicone when there is a high surface area structure to be released. Micro-fins are the worst possible structure for release as they have very high surface to volume ratios so there just isn't enough strength in the material to provide the elongation until release is accomplished from the sidewalls and there is the greatest possible holding force.
3) Use of a "lost wax" casting process involved using machinable wax which is a high precision, strong wax that can be directly machined. Silicone does release well from this wax, particularly in the presence of wax solvents, but tends to leave a residue on the silicone surface which will likely interfere with biocompatibility. Solvents for this was were available, but are very aggressive and contain carcinogens. While these solvents may possibly be driven off with heat, the uncertainty over biocompatibility is a major issue. Particularly within the microtubes, tiny amounts of an incompatible substance can have a major impact. Perhaps a more major issue is that this lost-wax process requires molding or cutting of the wax to begin with, which adds further to the issues of cost and/or release issues.

Re-Grouping:

At this point, the approaches were re-considered in view of more complete understanding of the pathway to clinical application outlined previously. It is unrealistic to envision a technology that would be produced in a single point, custom fabrication facility. The expense of running such a facility far exceeds the most optimistic revenues that could be generated, even if the entire developmental costs are absorbed by grants. At best, the MTA technology will become successful in a tiny market for high need individuals. While it is very likely that the MTA technology can be adapted to brain and spinal cord applications, for brain and spinal cord injury applications, in all, it is still a market that is several orders of magnitude smaller than the revenues could possibly support, even with worldwide distribution. Also, MTA technology is designed to support lifelike replacement limbs which will also be relatively high cost though perhaps more readily accomplished with available technology from advanced robotics efforts.

However, if standard CMOS foundry process technology can be leveraged, then perhaps the MTA approach has clinical promise within our generation with sufficient motivation. There are three critical developmental blocks that need to be accomplished in order to leverage this existing, high cost fabrication technology to enable clinical application of the MTA approach: 1) Post Processed CMOS (PPCMOS) foundry technology to provide bio-resistance and biocompatibility; 2) formation of microtubes on PPCMOS, preferably at wafer scale; and 3) 3D assembly of diced devices into implantable MTAs.

PPCMOS development:

Ongoing work under this grant has resulted in adaptation of CVD silicon carbide deposition with gold/iridium oxide upper level metal (developed at EIC Laboratories) that can be deposited onto finished CMOS foundry wafers. Processing is relatively straightforward and requires a minimum of readily available semiconductor equipment and cleanroom for processing. This can likely be contracted out now that the process details are defined.

For reference the electrode array design shown in the first annual report is repeated here.

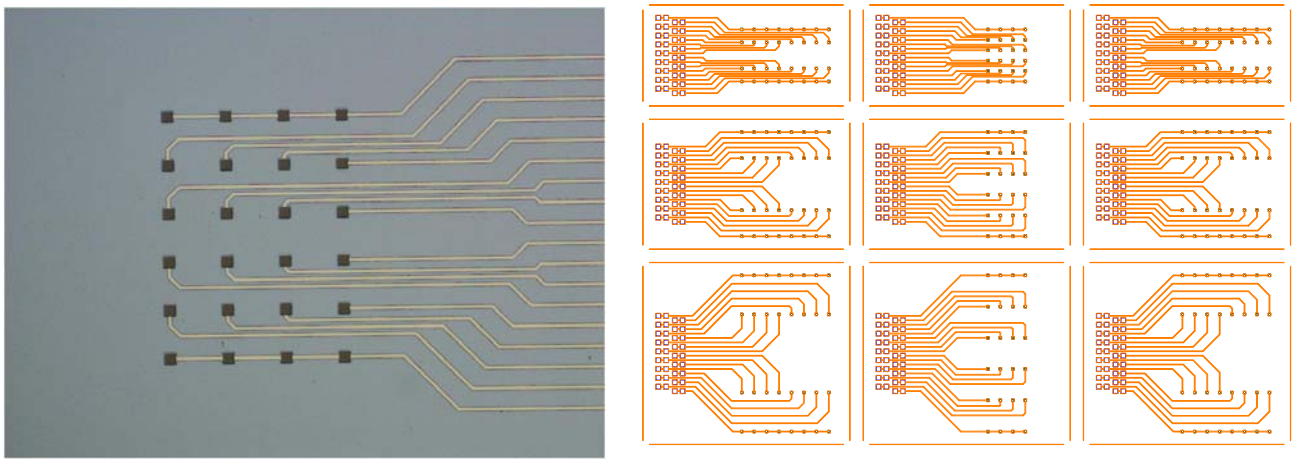

Figure 1: LEFT: Example electrode array (repeated from last year) showing iridium oxide electrode contacts on silicon substrate insulated with silicon carbide. Gold interconnects link gold wire bonding pads with electrode contacts. This particular design provides multiple differential pairs of electrodes for recording and/or stimulating within four 100um wide microtubes for detailed studies of electrode-axon-micro-tube interaction. Reference electrodes are ganged together along each end of the microtubes. RIGHT: Portion of mask layout showing overview of some of the designs to allow optimization of electrode configuration for CMOS IC micro-circuit compatibility, signal acquisition and signal input. Total tube lengths of 1.5mm, 2.5mm, and 3.5mm are possible with 50-200um microtube cross sections and either four sets of 4 independent electrodes or 8 sets of differential pairs. This small study will not allow full exploration of the design space. However, once one of these designs yields data, sufficient information will be available to suggest which design may be more effective.

The SiC/IrOx devices produced in collaboration with EIC Laboratories near the end of the last year exhibited poor adhesion of the metallization and could not be assembled. Because of the re-thinking of the project, the flexible substrate and interconnect afforded by using the polyimide based system was abandoned in favor of electrode arrays on silicon substrates that would serve as models for the CMOS substrates that would be necessary for the clinical system. A few adjustments of the adhesion layer for the gold and iridium layers were necessary this year. The new process sequence produces very high quality iridium electrode arrays on silicon substrates that are encapsulated with silicon carbide. These are very robust devices with gold bonding pads that exhibit high bond strength. The iridium electrodes activate reliably to iridium oxide, and will provide a stable, long term electrical interface to the axons within the microtubes. For electrical activation of axons for sensation and closed loop control, because of current constriction within the microtubes, these electrodes will be operated in controlled voltage mode for stimulation and will require very small currents (sub-microampere) for 10-100microseconds. This small charge transfer can be readily achieved capacitively through the iridium oxide which further ensures reliability and biocompatibility.

Bringing the SiC/IrOx to PPCMOS is an important milestone for the peripheral nerve interface field (though most of the technology was developed over the past several decades) because silicon carbide (SiC) can also provide an excellent long term barrier for sodium and other ions that can readily destroy CMOS integrated circuit (IC) function. Together with the multilayer passivations commonly in use for CMOS ICs, the SiC

overlayer should ensure that there are no changes to circuit function due to infiltration of ions for at least one hundred years, and perhaps much longer. Additionally, silicon carbide bonds well with medical grade platinum catalyzed silicones previously used for high quality encapsulation of the bond areas and interconnects for implantable microelectronics.

MicroTube Formation on PPCMOS ICs

As formation of fins on the backside, and stacking devices to form microtubes became unfeasible, methods for adding tubular structures to the active side of the devices was explored. Addition of microtubes to the PPCMOS ICs may ultimately be most readily accomplished through use of a planar, wafer scale process. Whether this can be done before or after wafer thinning depends on the final process. Ideally, a biocompatible thick film method will be developed, which would best be accomplished on wafer scale, before thinning and dicing. One of the most difficult challenges is preventing contamination of the material used to form the microtubes as even slight contamination can result in a tissue reaction that would occlude the microtubes. Possibly, use of a high purity, thick film poly-methyl methacrylate masked with chromium and ion milled could produce the necessary structure mandrels that could be dissolved following final assembly. Such fabrication technology is well within the capabilities of modern micro-fabrication facilities, but expensive to develop.

The material used to form the microtubes is also of critical importance. Platinum catalyzed silicones are being used for this project as those are the materials available and have performed well in the past. However, other materials such as undoped Spin On Glasses (SOGs) may be more appropriate for development of wafer level processes, but use of these requires additional facilities not readily available to InnerSea. An additional complication for use of SOGs is the nature of expansion/contraction of the material used for the mandrel as well as the SOG during curing and subsequent processing, which in itself could become a research project.

Ideally, the material used to form the mandrels for casting the microtubes on a wafer scale process would be left in place until the MTAs have been fully assembled. This will protect the inside of the microtubes from contamination during processing, and will mechanically protect them during 3D assembly. Under this ideal scenario, the mandrels would be dissolved in a final process step prior to sterilization.

One possibility for production of the mandrels is to use 3D rapid prototyping methods. Exploring this possibility led to some experiments done in collaboration with Stratasys, Inc using ABS plastic depositions. ABS is an attractive mandrel material because it is relatively inert but soluble in methyl ethyl ketone. While the theoretical limits of deposition capability were within those posed by the MTAs, in practice, since the deposition needed to be done directly on the silicon chip surface, adhesion of the molten ABS became problematic. This may have been due to a temperature or chemistry issue, but Stratasys R&D could not explore those issues without developing a funded project. Because the ABS must be directly deposited on a clean surface (to ensure adhesion of the overcoat material between the mandrels), there was no expedient method for improving adhesion. 3D prototyping methods are currently rapidly developing and will likely be able to handle the required geometries relatively soon. However, there will still be possible issues with maintaining the cleanliness between mandrels on the surface of the planar substrate. Vapors from the deposition process that could create just a monolayer of contamination are sufficient to compromise the bonding of silicones to the surface, so an overall process development effort will still be required.

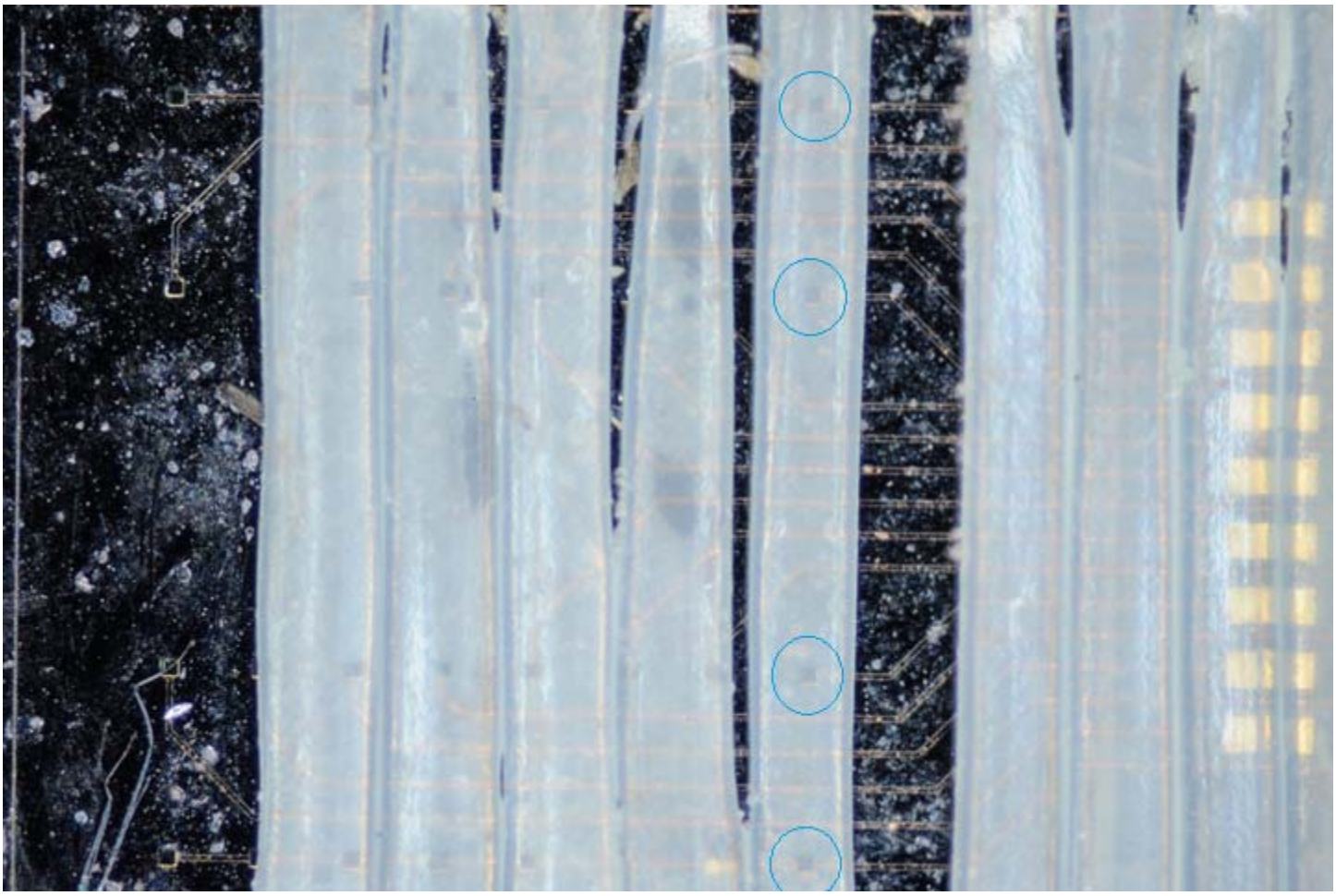

Figure 2: Example of attempted micro-extrusion of ABS onto SiC/IrOx electrode array. Resolution of the 3D system allowed deposition of 8 mil mandrels across the electrodes (4 are circled), but process was difficult to control due to poor adhesion to substrate. However, with the continuing development of 3D printing technology, this approach should become readily achievable soon.

Other 3D printing techniques have now become available (cross-linked starch based plastic for example from 3D Systems) that may yet provide a solution. However - resolutions are still limited; the substrate adhesion issue remains; and microtube contamination is possible depending on the exact materials and solvents used. As

3D printing becomes more refined and targeted at the micro-scale, it will become applicable to production of MTAs on wafer scale or individual chip basis, but the technology is not yet sufficiently mature.

3D Assembly of MTAs

The third block would involve 3D assembly of the chips into a full scale MTA. If the MTAs are constructed by use of sacrificial mandrels, on a complete wafer, then the wafers can be thinned, diced, washed, and assembled with the microtubes protected by the mandrels. Interconnection of the thinned die, while conceptually straightforward, poses several additional challenges including fragile substrates, clearing of bonding pads, and bonding each layer as the assembly is stacked. In our favor is that each layer does not need to be precisely aligned, but can be staggered with no great losses, and the interconnects are only power, ground and a data line, none of which are sensitive though leakage currents must still be avoided to protect the metallizations from corrosion.

Fortunately, for the latter consideration, well developed and understood silicone encapsulation methods exist to safeguard the connections once they are in place. If the wafer scale processing incorporated an etched pit in the middle of each of the three bond pads that becomes open and through when the wafer is thinned, then an alternating series of bonds may be sufficient for interconnection initially, but it may be more efficient to use bump bonding or electroplating to form the final connections once the process is fully developed.

Current Research on MTA Production:

Because of the shortcomings of all the previous approaches, particularly when considered for clinical devices, an expedient manual method for producing the microtubes is currently being developed. This method is relatively simple, and can be implemented in a laboratory with minimal resources. Basically, it is a casting method that uses monofilament threads to form the mandrels. Simple tests were done to see if this approach could in fact be accomplished and an example is shown in Figure 3.

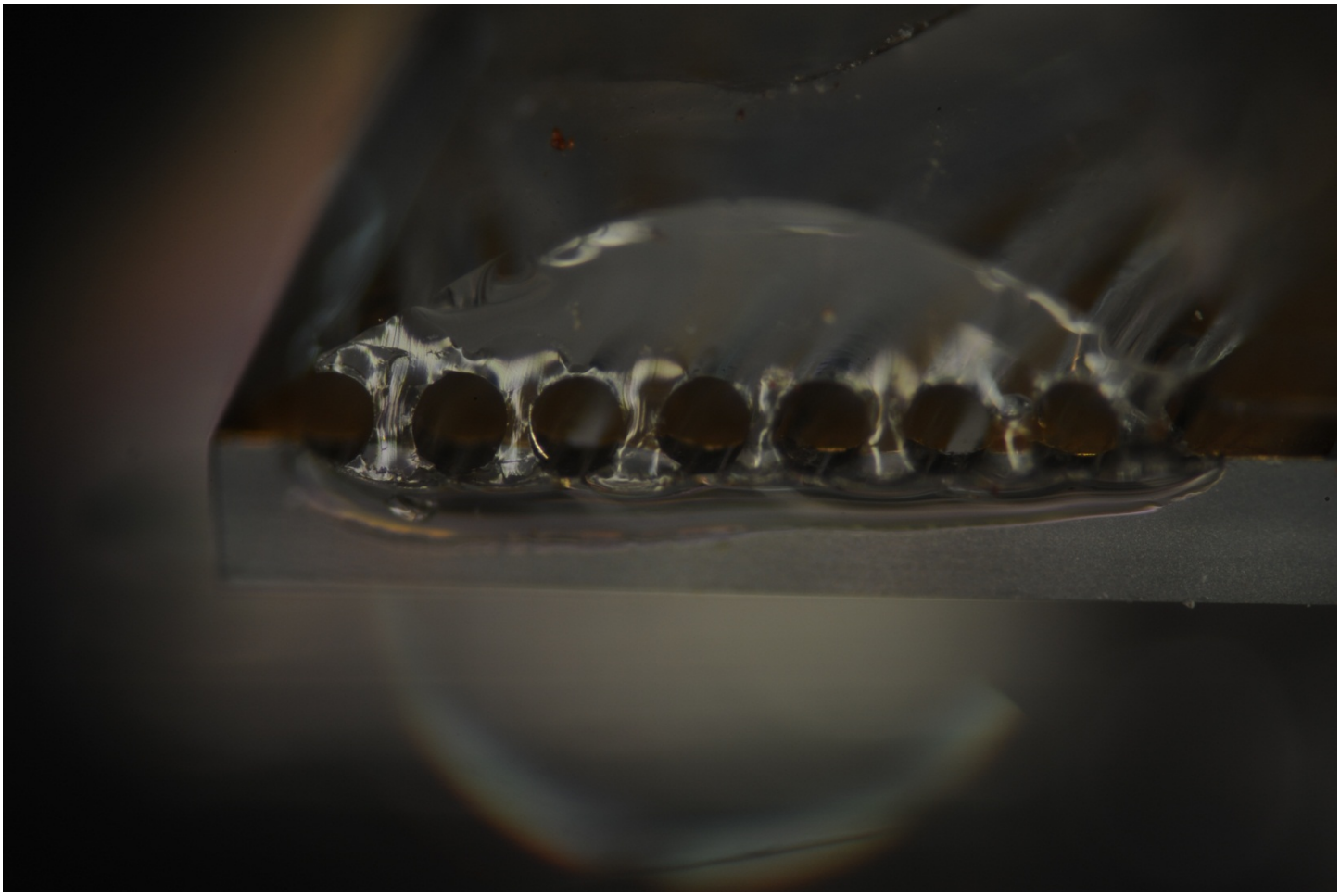

Figure 3: Cross section of cast silicone microtubes with filaments removed. This was a gold patterned glass substrate used for developing the method. Microtubes are 200um diameter separated by about 50um.

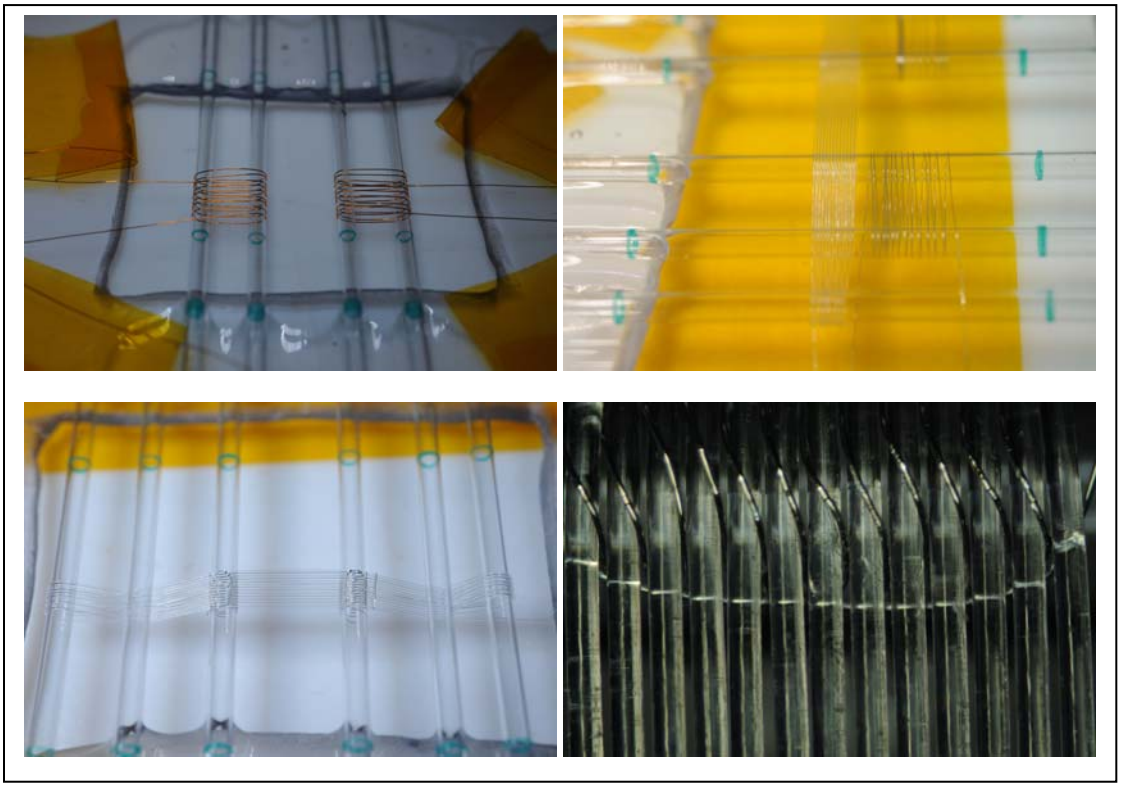

Figure 4: Examples of filament method for casting microtubes onto surface of SiC/IrOx electrode arrays. Top left is an example of using fine dimension copper wire (75um) to provide spacers for subsequent wrapping of monofilament. Top right and bottom left show an alternate method using 50um platinum wire to provide spacing between filaments. Bottom right shows final set with relatively uniform spacing between filaments, but all spacings are slightly larger than 50um because of residual springiness of platinum. Smaller platinum or smaller filaments will result in the 240um c-c spacing designed into the electrode arrays.

The principal concern with this approach is developing a method that will ensure that the surfaces of the electrodes are protected during infiltration and curing of the silicone. The following problems are being addressed: creating the array of precisely spaced threads that are co-planar; setting the threads onto the substrate with precise alignment; and sealing the underside of the thread to the silicon carbide surface (temporarily) while a silicone cast is made and cured. This last problem is more difficult than it may seem as platinum catalyzed silicones are very sensitive to any material that interferes with the catalyst, the material should be biocompatible or readily and completely removed, and the material must also provide enough wetting of the silicon carbide surface to spread along the mandrel, but have enough surface tension so it does not spread between the mandrels.

Plans for 2 Month Extension

1. Fabricate an MTA on silicon carbide electrode array with new processing.

2. Evaluate current process technology alternatives for future work and clinical applications.

KEY RESEARCH ACCOMPLISHMENTS:

- Percutaneous connectors, wire bonding interface, electronics adapters, and encapsulation methods useful for MTA prototypes and pilot clinical studies were created.
- A silicon carbide/iridium oxide based post-process sequence to enable implantation of MOS based integrated circuit electrode arrays was developed in collaboration with EIC Laboratories.
- Microelectrode arrays for use in studies of the electrical properties of implanted MTA arrays were fabricated.
- A casting method was developed to produce MTAs on any silicon MOS circuit - chip or wafer scale.
- System design for a clinical device was accomplished.

REPORTABLE OUTCOMES:

Submission of paper in IEEE transactions on MTA/silicon carbide electrode array fabrication techniques for high resolution peripheral nerve interface.

CONCLUSION:

Sufficient progress in this field has demonstrated that the high resolution peripheral nerve interface is feasible, and current technology is sufficiently developed to realize a clinical system. Interaction with discrete neural channels of peripheral nerves is sufficiently complex that it is advisable to use human volunteers who can understand the necessary motor tasks and learning, and who are able to respond with verbal descriptions of the effects of sensory inputs. Risks are minimal as only the severed end of peripheral nerve is at risk, and the devices can be readily removed if necessary by trimming the regenerated nerve tissue. While in most work, benefit to the actual volunteers are minimal or not possible, in this case, once the implanted system is in place, the majority of further developments will be software and external electronics. The volunteers will gain use of natural control and sensory pathways that are not currently possible, providing enhanced, natural control of existing powered prostheses.

REFERENCES: None

APPENDICES: None